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Integrating data, expert opinion and fuzzy logic in the development of an index of wetland condition

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Abstract. Wetlands face an intensifying level of degradation, and management to protect their extent and character is paramount. To support wetland management in south-east Australia, we developed a wetland condition assessment tool for palustrine and lacustrine wetlands. Through extensive consultation with end users during its development, the tool, the Index of Wetland Condition (IWC), considers user needs and skills, as well as attempts to assess the complex nature of wetland systems and their inherent variability, both spatially and temporally. The IWC is structured as a hierarchical index with 13 indicators nested under six characteristics (subindices) that influence wetland function: wetland catchment, physical form, wetland soils, water properties, hydrology and biota. The contribution of each to the overall index (scored along a condition gradient) was estimated from quantitative biological and physicochemical data from 24 wetlands using a fuzzy cognitive map approach. The IWC development framework will be particularly useful in jurisdictions globally where reference condition information is limited or lacking for indicators, or where there are substantial practical constraints that limit the selection of indicators, such as management staff capability or capacity. Uptake of the IWC with wetland practitioners in south-east Australia has been substantial.

Keywords: condition index, fuzzy cognitive map, management, practical considerations, reference condition, wetland.

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Introduction

Wetlands are important habitats for biodiversity and provide many ecosystem services, including regulation of extreme events associated with climate change, biogeochemical cycling that is contributing to improved water quality and cultural services (Millennium Ecosystem Assessment 2003; Maltby *et al.* 2013; Meli *et al.* 2014). However, wetlands globally face an intensifying level of degradation from human activities (Davidson 2014; Finlayson *et al.* 2017). The most significant impact of these activities has been the complete loss of wetlands in some landscapes (Ausseil *et al.* 2011; Davidson 2014; Darrah *et al.* 2019).

Measuring the level of degradation in complex systems such as wetlands is difficult because of their dynamism and spatiotemporal variability. This is especially so for wetlands in Mediterranean climates (Ortega *et al.* 2004; Rouissi *et al.* 2014). In addition, wetland managers are often constrained in effectively monitoring and assessing these systems because of limited resources and expertise (De Leo and Levin 1997; Kotze *et al.* 2012). Condition assessment methods aim to summarise the massive complexity in wetland function and provide a simple measure or suite of measures that can be used to monitor changes in wetland components and function over time (Gardner and Davidson 2011; Finlayson *et al.* 2017). Approaches to developing condition assessment methods include an assessment of:

- the whole wetland, using indicators based on wetland characteristics and components (e.g. soils, hydrology, biota) or specific biotic groups, such as invertebrates or fish (see Roth *et al.* 1996; Spencer *et al.* 1998; Ladson *et al.* 1999; Bolton 2003)
- the whole wetland, using indicators based on impacts or threats known to damage wetlands (see Brooks *et al.* 2017; Clarkson *et al.* 2003)
- specific biotic groups as a surrogate for wetland condition (see Davis *et al.* 1999; Chessman *et al.* 2002)
- the condition of higher-level wetland biotic groups (such as fish or amphibians) rather than wetland condition (e.g. United States Environmental Protection Agency 2002; Mack 2007).

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Wetland condition assessment methods have been developed in many countries and regions to address local wetland management needs and international reporting obligations. The US has an abundance of such methods in various jurisdictions (Fennesy *et al.* 2007), with approaches typically targeted at specific wetland types (see Fennesy *et al.* 2007; Martínez-López *et al.* 2014) and using large ecological datasets. In some contexts, for example when there is a need for broad-scale condition assessment and ecological data are limited, expert elicitation combined with modelling approaches using the available ecological data can maximise the integrity of the method.

In south-eastern Australia, there is an increasing need to be able to assess the condition of wetlands to enable surveillance monitoring for management purposes and to meet national and international reporting obligations. Scrutiny of wetland condition assessment methods that have been developed and adopted globally (Department of Sustainability and Environment 2007) or in parts of south-east Australia (Spencer *et al.* 1998) reveal they cannot be directly applied or adapted because of constraints on the availability of ecological data, resources and expertise.

This paper describes the development of an index to address this need, namely the Index of Wetland Condition (IWC). The IWC is relevant to palustrine and lacustrine wetlands (Ramsar Convention 2005) and its development framework used an approach that managed the limited data available using expert elicitation and fuzzy cognitive maps (FCMs). FCMs are graphical models related to Bayesian networks and artificial neural network models (Kosko 1992). FCMs encode relationships among variables of interest using a directed graph where the nodes represent variables or concepts of interest and the links or 'edges' between nodes represent cause-and-effect relationships (Kosko 1986). Such models have previously been used in ecology to model causal relationships among species or guilds to represent community structure (Hobbs *et al.* 2002; Ramsey and Veltman 2005; Ramsey and Norbury 2009). Because FCMs can encode qualitative relationships between variables, they are ideally suited to model relationships among wetland condition measures, especially where such measures consist of qualitative expressions of condition, which may be derived from expert opinion.

We describe the core characteristics of the IWC, the assessment of its indicators and the relative importance and contribution of the indicators to overall wetland condition. The current and potential uses of the index, future enhancement and application are also presented. We also highlight potential situations where the processes used in the development of the IWC could inform the design and implementation of analogous monitoring programs.

IWC design

The design of the IWC followed four key steps: (1) the development of a conceptual model of wetland function to underpin the index structure and framework; (2) identification of indicators, sourced from the literature and filtered in consideration of the practical requirements of end users and the ecological requirements of the index; (3) the development of an indicator scoring system and assigning a level of confidence to the indicator assessment; and (4) using expert elicitation and a FCM framework to identify the relative contribution of each characteristic to the overall IWC and determining the linguistic categories for condition scores.

Development of a conceptual model of wetland function

Wetland condition was defined as the 'state of the biological, physical and chemical components of the wetland ecosystem and their interactions'. This is the definition used by the Ramsar Convention to describe 'ecological character' (Ramsar Convention 2005). A simplified conceptual model of wetland function, adapted from Mitsch and Gosselink (2000), was used to identify the core characteristics of the IWC and its components that were applicable to all wetlands in its geographical scope. We recognise that this model (Fig. 1) is simplistic, but its primary

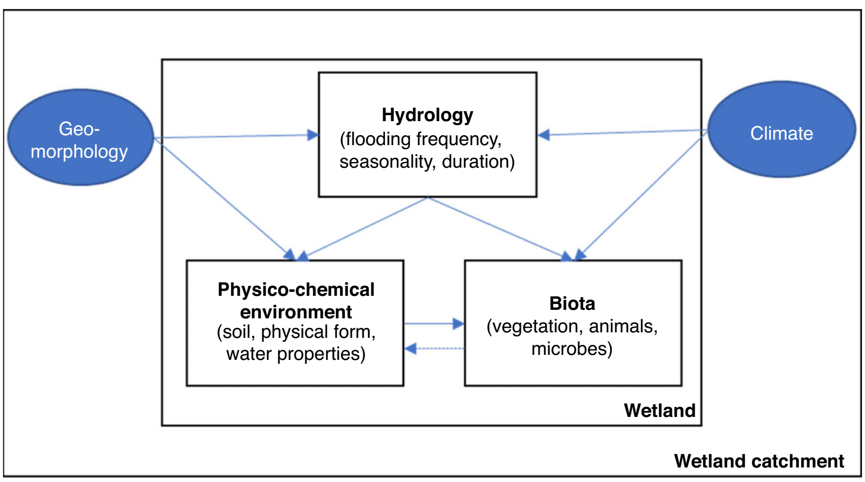

Fig. 1. Conceptual diagram showing the key characteristics of all wetlands (hydrology, physico-chemical environment, biota, wetland catchment), key wetland drivers, geomorphology and climate, and the relationships between them. Reprinted and adapted with permission from the National Research Council (1995) by the National Academy of Sciences, courtesy of the National Academies Press, Washington, DC, USA.

purpose was to define the most critical characteristics of wetland function: hydrology, physicochemical properties, soils and biota. We added the adjoining wetland catchment to the model because it has a marked influence on condition for many wetlands in the study area (Fig. 1).

Indicator selection and filtering

Indicators that measure specific components of each wetland characteristic were identified from an extensive list of candidates sourced from the wetland assessment literature (Spencer *et al.* 1998; Davis *et al.* 1999; Chessman *et al.* 2002; United States Environmental Protection Agency 2002; Bolton 2003; Clarkson *et al.* 2003; Ortega *et al.* 2004; Mack 2007), an assessment of threats to wetlands in Victoria (Department of Sustainability and Environment 2005) and consultation with wetland experts (Table 1). Specific indicators for each component of each wetland characteristic are listed in Appendix 1. Indicators were included based on whether they could be practically applied and whether reference condition could be determined from the literature and available ecological data. For components for which no reference condition is available, reference condition is inferred as the absence of threats operating on the components (based on an assessment of threats at the site).

The applicability of the candidate indicators was assessed according to criteria obtained from the literature, and adjusted to take into account the practical and ecological requirements of the IWC.

Breckenridge *et al.* (1995) and Jackson *et al.* (2000) suggest that indicators should be applicable and readily interpretable across different regions, correlate with changes in ecosystem processes, encompass temporal and spatial variability and be responsive to change.

In addition to these criteria, whether an indicator exhibited a known reference condition and optimally complemented other indicators in describing the complexity were also considered key criteria. The fundamental reference condition adopted by the index was a wetland in its natural state, free of human disturbance, at the time of European settlement (i.e. within the past 200 years; Ladson *et al.* 1999; Downes 2006). The reference condition for each indicator was specified or informed by the wetland literature (Castelle *et al.* 1994; Davies and Lane 1995; Boyd 2001), expert opinion and wetland plant data. For vegetation indicators, reference condition was regionalised using a wetland vegetation typology with 151 ecological vegetation classes (EVCs). The classes have indicator species and are designated based on overall vegetation structure. Mapping of these vegetation classes is not required for application of the indicators because EVCs can be identified on-site (Department of Environment, Land, Water and Planning 2018).

Cost-effectiveness and consideration of labour, equipment, analytical and data analysis costs were identified by Breckenridge *et al.* (1995) and Jackson *et al.* (2000) as important practical considerations for indicators. Practical requirements of the IWC, identified from extensive consultation with end users (wetland managers and regional planners from across the state), were threefold: feasibility within short timelines, requiring modest financial resourcing and not placing excessive demands on staff expertise. This meant that for maximum uptake the index needed to be feasible at any time of year (regardless of the wetland hydrological phase), able to be completed in a single visit, easy to implement and able to provide results that could be easily interpreted by planners and managers with limited expertise. It was also intended that the index could be applied to individual wetlands to identify long-term (>10 years) trends

Table 1. Candidate indicators for the various components of each wetland characteristic

For a full list of candidate indicators, see Appendix 1

Wetland characteristic	Wetland component	Number of indicators identified
Wetland catchment	Wetland catchment	4
	Wetland buffer	2
Physical form	Area of the wetland	1
	Wetland form	3
Hydrology	Water depth; and frequency, duration and timing of inundation	3
Water properties	Nitrogen	1
	Phosphorus	2
	Electrical conductivity (salinity)	6
	Turbidity	2
	Temperature	2
	Dissolved oxygen	1
	pH	4
	Nutrient cycling	1
Soils	Soil physical properties (structure, texture, consistency and profile)	3
	Soil chemical properties (organic content, nutrients, metal oxides, silica clays, salts and pH)	6
	Soil biological properties (soil organisms such as bacteria, fungi, protozoans, nematodes, mites and worms)	2
Biota	Vertebrate fauna (fish, amphibians, reptiles, waterbirds and mammals); aquatic invertebrates; phytoplankton; diatoms	5
	Wetland vegetation (macrophytes)	4

in condition (Department of Sustainability and Environment 2005).

Taking into account both the ecological and practical requirements of the IWC, the resultant IWC indicator assessment criteria:

- were applicable to all wetlands in the region (Australian jurisdiction of Victoria)
- were repeatable and suitable at any time of year
- involved a single measurement able to be taken per year (the indicator not being temporally variable over the course of the year)
- were responsive to changes over 3- to 5-year timescales (a time step considered suitable for the intended use of the IWC, and the Ramsar reporting cycle; Davidson *et al.* 2020)
- yielded results that were easy to interpret
- could be compared with a known reference condition or an assessment of threats operating on the component that could be assessed
- optimally complemented the already chosen indicators in describing complexity.

Assessed against these criteria, the final list of indicators (Table 2) consisted of either direct measures of the components or processes themselves (e.g. wetland soil disturbance, wetland plant life forms, wetland weed cover) or measures of threats to the components. The latter are sometimes referred to as surrogate indicators (Kent *et al.* 1992; Spencer *et al.* 1998). The characteristics to which the indicators belong form the top tier of the index structure (i.e. its subindices).

Scoring indicators and assigning a level of confidence to their assessment

For all indicators, the greater the departure from the reference, the lower the score. For example, for the 'buffer width' indicator, the reference condition was defined as >50 m, which reflected the maximum buffer scores in other condition assessment methods (Castelle *et al.* 1994; Boyd 2001; Mack 2007). In the IWC, a maximum score is thus obtained for an average buffer width of >50 m, whereas a minimum score is obtained for an average buffer width of <5 m (Table 3). The scoring framework for each is presented in an excerpt from Department of Environment, Land, Water and Planning (2019) in the Supplementary material (Fig. S1).

To maximise confidence in the assessment of the indicators, multiple lines of evidence of impacts were included in the assessment. For example, to assess the indicator for nutrients,

Table 2. Final selection of indicators for the components of each subindex in the Index of Wetland Condition (IWC), with corresponding reference condition

Subindex	Wetland component	Indicator	Indicator type	Reference condition
Wetland catchment	Wetland catchment	Land use intensity	Surrogate	Absence of disturbance
	Wetland buffer (fringing native terrestrial vegetation)	Average width of the buffer	Direct	Derived from literature (Table 3)
		Percentage of wetland perimeter with a buffer	Direct	100% of wetland with buffer
Physical form	Area of the wetland	Percentage reduction in wetland area	Direct	No change in extent
	Wetland form	Extent and severity of change in bathymetry	Direct	No evidence of change in bathymetry
Hydrology	Water regime	Severity of change in water regime	Surrogate	No evidence of change in water regime
Water properties	Macronutrients (e.g. nitrogen and phosphorus)	Severity of nutrient enrichment	Surrogate	No observed change or threats to nutrient enrichment
	Electrical conductivity (salinity)	Severity of change in salinity	Surrogate	No observed change or threats to salinisation
Soils	Soil physical properties (structure, texture, consistency and profile)	Percentage and severity of wetland soil disturbance	Surrogate	No evidence of soil disturbance
Biota	Wetland plants	Wetland vegetation quality assessment based on:	Direct	EVC typology (Department of Environment, Land, Water and Planning 2018)
		• critical life forms	Direct	
		• presence of weeds	Surrogate	
		• indicators of altered processes	Direct	
		• vegetation structure and health	Direct	

Table 3. Buffer functions and suggested widths required for protection of a wetland

From Castelle *et al.* (1994), Davies and Lane (1995) and Boyd (2001)

Role of buffer	Buffer width needed to perform function
Protection of inflowing surface water quality (sediment and nutrient trapping)	As little as 6 m for low overland flow velocity
Maintenance of ecological processes and major food webs	20–50 m
Protection of inflowing groundwater quality	≥250 m

'severity of change in nutrient enrichment', all the activities that contributed to it (point source discharges, diffuse run-off, grazing by livestock, grazing by feral animals, application of fertiliser, aquaculture) and any evidence of it (algal blooms, nutrient data) needed to be documented and considered. This approach was used for surrogate indicators in the hydrology, physical form and soils characteristics.

Weighting the subindices and developing linguistic categories of condition

The overall IWC score is represented as the sum of the six contributing subindices as a weighted sum:

$$\mathrm{IWC} = \sum_{i=1}^{6} w_i S_i \tag{1}$$

where w_i are the weights and S_i are the scores for each of the i characteristics ($i = 1 \ldots 6$). The weight represents the relative importance of each characteristic (subindex) to the overall IWC.

Expert elicitation based on quantitative data was used together with condition data obtained from the IWC in a FCM framework to identify w_i and linguistic categories of condition (excellent, good, poor). Nine wetland experts with a range of wetland ecology backgrounds (invertebrates, water chemistry, wetland vegetation and amphibians) participated in the process. Each expert was provided with intensive ecological datasets, land use mapping and aerial imagery from 24 wetlands in western Victoria that had been assessed using the IWC method. The level of disturbance and condition of these wetlands were representative of those across the broader study region. The ecological data, which included geomorphology, soils, electrical conductivity, pH, nutrients, turbidity, wetland plants, birds, frogs, diatoms, rotifers, zooplankton and macroinvertebrates, were used by the experts to assign a condition score on a scale from 1 to 10 for each of the wetland subindices (e.g. biota, hydrology, soils) and overall condition. Experts also classified their scores for individual subindices and the overall score as 'poor', 'good', 'very good' or 'excellent'. Experts each assessed between 11 and 16 wetlands, with each of the 24 wetlands receiving between 4 and 6 assessments. The resulting training data consisted of total of 111 assessments.

The weights for each of the subindices were estimated from the expert opinion data using a FCM. As noted earlier, FCMs are graphical models related to Bayesian networks and artificial neural network models and encode relationships between variables of interest using a directed graph in which the nodes represent variables or concepts of interest and the links or 'edges' between nodes represent cause-and-effect relationships (Kosko 1992). A FCM model was constructed to represent the IWC index as the output node and the six subindices as input nodes (Fig. 2). Each of the edges connecting each subindex and the IWC represented the (weighted) influence of that characteristic on the IWC.

The model was fitted to expert opinion data to determine the appropriate edge weights for each of the subindices. Because the scoring of each component and the overall IWC was a subjective exercise, there was some uncertainty or 'vagueness' in the assessment. Vagueness results when the score for a component

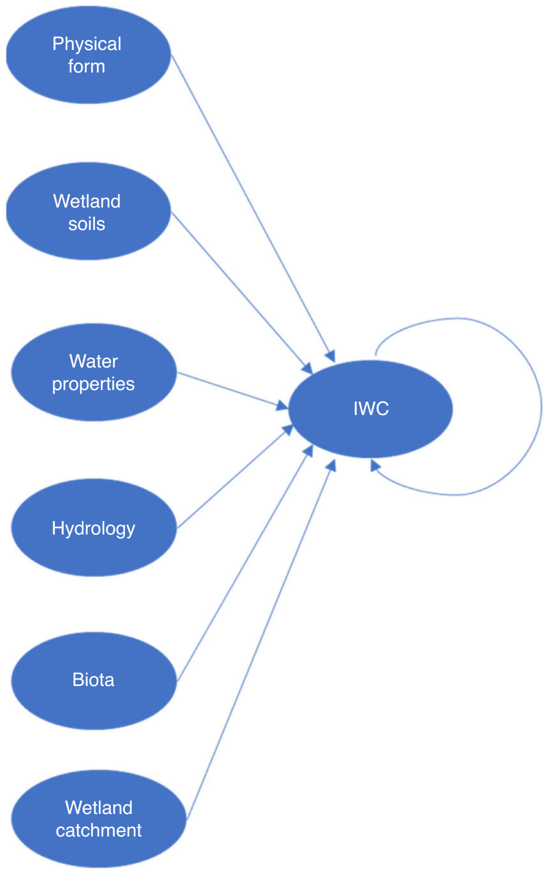

Fig. 2. A fuzzy cognitive map (FCM) model of the Index of Wetland Condition (IWC). The nodes represent the subindices and the overall IWC in the model. The arrows (edges) connecting the nodes to the IWC represent a weight. The arrow connecting the IWC with itself represents 'entropy' or the tendency for a wetland to degrade in condition in the absence of inputs.

(e.g. the value 'good') is interpreted slightly differently by different experts. To handle this vagueness, we used fuzzy logic, the mathematics behind computing with language (Zimmermann 1996).

Fuzzy sets explicitly model the relationship between vague linguistic descriptors used to describe the 'state' of a component and the resulting score assigned to that component. This process, known as fuzzification, takes values (e.g. scores) and classifies them into an arbitrary number of categories or sets (e.g. 'low' or 'high'). Unlike ordinary sets that have 'hard' boundaries, fuzzy set boundaries are 'soft', reflecting uncertainty in the boundary of the set. This means a score can belong to more than one set.

Fuzzy sets were constructed to represent each of the four linguistic classifications of condition ('poor', 'good', 'very good', 'excellent'; Fig. 3). The linguistic classifications, as well as the upper and lower boundaries of each set, were elicited by expert opinion and represent an estimate of the 'vagueness' around each linguistic classification for a given score. Hence, based on expert opinion, wetlands with an index score of 9 or 10 definitely represent wetlands in 'excellent' condition, but, if the score is <7, it is considered that the wetland is definitely not 'excellent'. Thus, scores between 7 and 9 represent wetlands that are 'somewhat' or 'partially' excellent. Because each fuzzy set

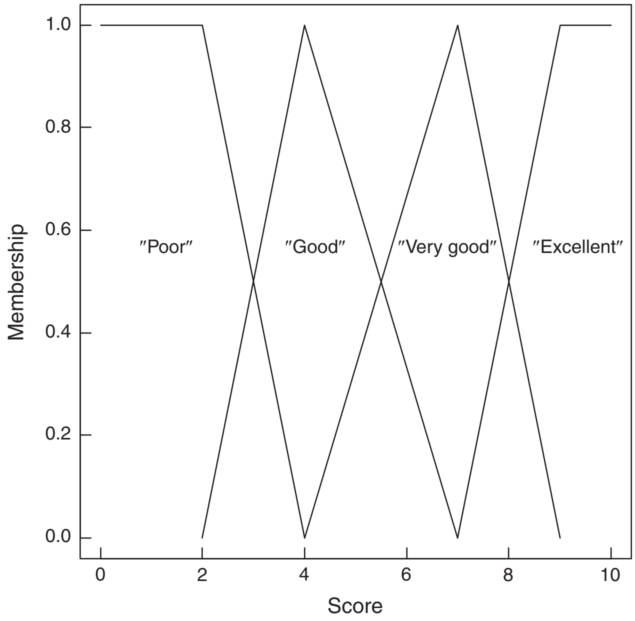

Fig. 3. Fuzzy sets classifications used to classify scores for each of the wetland characteristic and the overall Index of Wetland Condition (IWC). Note that the area beneath the curves represents the linguistic approximation.

has overlapping boundaries, scores of 7 and 9 also partially belong to the fuzzy set 'very good'. Hence, any score can be represented by a membership function representing the vector of membership values of each set for that score. Another feature of the fuzzy set procedure used here is that these fuzzy set membership values can be integrated to calculate a single (fuzzy) output value (called 'defuzzification'). This value is called a 'fuzzy score' and is an approximate number. Hence, a fuzzy score of 5 is interpreted vaguely (e.g. 'about 5'). Both the 'fuzzy set' (linguistic approximations of 'poor', 'good') and 'defuzzified' scores were produced from our model to predict the overall IWC.

Training the model

To train the model, single observations from the training data, consisting of scores for each of the six individual subindices, were 'fuzzified' and entered into the model. The overall IWC score was then predicted by 'defuzzification', again using the fuzzy sets. This was repeated for each of the observations in the training dataset. For a training dataset consisting of *n* observations, the predicted IWC scores were compared with the observed (expert-elicited) IWC score by calculating the 'fitness':

$$fitness = \frac{1}{\sum_{i}^{n} (IWC_p - IWC_o)^2 + 1}$$

where IWC_p is the predicted IWC score and IWC_o is the observed IWC score. The objective of the training was to find the edge weights for the FCM model that have maximum fitness. Using a stochastic global optimisation routine based on a particle swarm algorithm (e.g. Petalas *et al.* 2009), estimates of the best-fitting edge weights for the FCM were determined. The problem of over-training bias, a phenomenon in which the model predicts the observed data at hand well but predicts new data poorly, was reduced using a cross-validation procedure. To do this, a portion of the training data was left out and the model was trained on the remaining data with predictions then made on the data left out (the prediction set). This cross-validation procedure was repeated using five subsets (folds) of the data with the model used to predict both the IWC score and score class category for each of the prediction sets. Two measures of predictive accuracy were used to assess model fit, namely linguistic accuracy and relative bias, defined respectively as:

$$LA = \sum_{i=1}^{n} \frac{f(i)}{n}$$

and

$$RB = \frac{\sum_{i=1}^{n} \left| \frac{\hat{x}_i - x_i}{x_i} \right|}{n}$$

where LA is the measure of linguistic accuracy, defined as the sum of the correctly predicted score categories $f(i)$ divided by the total number of predicted observations (n). Relative bias (RB) was calculated as the mean of the relative bias estimates between predicted and observed IWC scores (see Stach *et al.* 2008).

Measure of accuracy and edge weights for subindices

The overall linguistic accuracy was 72%, meaning the model predicted the correct score category (e.g. 'good', 'poor') 72% of the time, on average. Estimates of relative bias were low, with a mean error of 11% (i.e. the predicted IWC score differed by an average of 11% from the observed IWC score).

The overall best-fit estimates of the edge weights for each subindex, averaged over the five training sets, ranged from 0.07 for soils to 0.73 for biota (Table 4). These were adopted as the weights for each subindex, used in the calculation of the overall IWC score.

Discussion

Many of the world's wetlands are vulnerable to threats from many aspects of human civilisation, and large losses of wetlands have occurred globally (Davidson 2014). Wetlands that remain in the landscape are being degraded by a multitude of threats, especially those in agricultural and urban settings. Identifying and mitigating these threats is often a focus of wetland management. Key to this is an understanding of the impacts of threats on wetland components and the actions needed to mitigate them. The IWC was developed considering all wetland components and the threats operating on them.

IWC development used a systematic, transparent process in determining its structure and indicators that included filtering candidate indicators through the practical requirements of end users and the ecological requirements of the index. Expert elicitation (with multiple experts and datasets) and a FCM approach were used to assess the relative importance of the

Table 4. Construct of the Index of Wetland Condition (IWC) with estimates of the edge weights (w_i) for each wetland subindex derived from the FCM model fitted to the expert opinion training data

Subindex	w_i	Wetland component	Indicator
Wetland catchment	0.26	Wetland catchment	Land use intensity
		Wetland buffer (fringing native terrestrial vegetation)	Average width of the buffer
			Percentage of wetland perimeter with a buffer
Physical form	0.08	Area of the wetland	Percentage reduction in wetland area
		Wetland form	Extent and severity of change in bathymetry
Hydrology	0.31	Water regime	Severity of change in water regime
Water properties	0.47	Macronutrients (e.g. nitrogen and phosphorus)	Severity of nutrient enrichment
		Electrical conductivity (salinity)	Severity of change in salinity
Soils	0.07	Soil physical properties (structure, texture, consistency and profile)	Percentage and severity of wetland soil disturbance
Biota	0.73	Wetland plants	Wetland vegetation quality assessment based on: • critical life forms • presence of weeds • indicators of altered processes • vegetation structure and health

IWC indicators and to identify weights for each characteristic. The use of this approach, although common in other applications (Kahraman *et al.* 2003, 2006), has thus far been limited in the context of wetland condition assessment (Fennesy *et al.* 2007; Chatterjee *et al.* 2015). Therefore, many existing tools have assumed that indictors have an equally important contribution to wetland condition. Through a FCM approach, we identified that wetland plant indicators were relatively more important than wetland physical form (bathymetry) or soil indicators. This can be attributed to the comprehensive wetland plant typology that underlies the assessment of the plant indicators.

Managing constraints

The IWC approach balanced practical and ecological requirements, which meant that some important constraints needed to be overcome. The need to apply the index at any time of year (regardless of the wetland hydrological phase) in a one-off measurement and the lack of a regionalised reference condition limited the number of direct measures for several indicators. In the 'water properties' characteristic, direct measures of nutrients and salinity could not be used because many wetlands are seasonally dry, and multiple measurements are required to account for their large-magnitude temporal variation (particularly for seasonal wetlands). Surrogate indicators were therefore selected and, to maximise the confidence in these measures, we adopted a multiple-lines-of-evidence approach. A supplementary benefit of explicit assessment of threatening activities is that managers can also use this information for 'threat' identification.

Knowing the reference condition for each indicator is critical for the overall assessment of condition (Anderson 1991; Ladson *et al.* 1999; Downes 2006; Herlihy *et al.* 2008). A wetland typology takes account of spatial variability among wetlands from different landscapes (Fennesy *et al.* 2007) and is a useful approach for land use, physical or chemical reference criteria (Herlihy *et al.* 2008; Hawkins *et al.* 2010). Other than for vegetation (Department of Environment, Land, Water and Planning 2018), an appropriate typology was not available to assist with the determination of reference condition for many indicators and, as such, many were set as the absence of any impacts.

IWC use and future development

Following training in the practical and theoretical aspects of the IWC, its uptake and application has been substantial. It has been used by more than 20 natural resource management and government agencies, which has resulted in an assessment of more than 1600 wetlands (Papas and Moloney 2012). Predominant uses have been measuring changes in ecological character for Ramsar reporting obligations (Ramsar Convention 2005), identifying threats and impacts to wetlands and benchmarking wetland condition to examine longer-term trends in response to threat mitigation (e.g. livestock grazing, changes to the wetland water regime). The IWC has also been adopted as one of several metrics in a formula that assesses return on investment (condition gain) from proposals by private landholders to improve the condition of wetlands on their properties.

Considering its current limitations, future development of the index should seek improvements to reference condition regionalisation at broad and fine scales. A new wetland typology for wetlands in Victoria has been developed (Department of Environment, Land, Water and Planning 2016), which could support regionalised reference conditions for some indicators for certain wetland types (e.g. salinity concentrations in alpine wetlands). At a finer scale, Hawkins *et al.* (2010) recommend site-specific determinations for reference conditions based on predictive models. This approach has been found to be useful in other regions (Mazor *et al.* 2016; Stein *et al.* 2017).

A study is presently under way in Australia characterising water regimes of wetlands from surface water detection over the life (from 1987 to present) of the Landsat Thematic Mapper sensor (Mueller *et al.* 2016; Dunn *et al.* 2019). These data have the potential to validate or update the new wetland typology and define reference hydrological conditions for the new wetland types.

Application of the IWC development framework

The IWC was needed for a broad-scale assessment of wetland condition to meet regional and international reporting obligations and to assist wetland management. In addition, a key outcome of the use of the index across the region has been an increased awareness of wetlands by agencies and the community, the threats that affect them and wetland conservation on public and private land tenure. To improve discrimination in condition categories for reporting purposes, a richer set of linguistic descriptors ('very poor', 'poor', 'moderate', 'good' and 'excellent') were adopted before implementation of the IWC. Assignment of scores to these categories is unconnected to the approach and linguistic descriptors used by the experts for determination of subindex weights.

The systematic and transparent process used in the IWC development framework considers data limitations and end user requirements while employing extensive consultation with end users. In regions where limited financial resources and management capability are constraints to meeting obligations such as reporting on changes in ecological character of Ramsar wetlands (Davidson *et al.* 2020), the IWC development framework could be considered to meet these needs.

Indicators from five of the IWC's six subindices can be applied to any palustrine or lacustrine wetland globally, and although the vegetation indicators are linked to a regionalised vegetation typology, the indicators themselves (life forms, weeds, indicators of altered processes, vegetation structure and health) are relevant to any wetland plant typology.

The development style of the IWC, combining data, expert elicitation and fuzzy modelling, has not commonly been used for this type of application, and as such represents a novel approach in this context. Although the method investigates and assesses wetlands, there is a similar need for condition information for other ecosystems, such as rivers, estuaries, forests.

The IWC framework will be directly useful in the following situations: threat identification; where broad-scale condition assessment of wetlands is required (encompassing multiple systems); where the reference condition of some wetland components and indicators may be limited; and where there are substantial practical constraints, such as in management capability or capacity.

As human disturbances continue to threaten ecosystems, there is an ongoing need for the continued development of approaches to assess ecological condition. The development and construction of these approaches should be tailored to the particular needs and contexts and should consider their practical implementation.

Availability of data and material

All data and materials, and custom code comply with field standards. The expert elicitation and Index of Wetland Condition data that support the findings of this study are available from the Arthur Rylah Institute, Department of Environment, Land, Water and Planning (research.ari@delwp.vic.gov.au).

Conflicts of interest

The authors declare that they have no conflicts of interest.

Declaration of funding

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Appendix 1. Candidate indicators for each wetland characteristic and component

Direct measures are measures of the components or processes themselves, and surrogate measures are measures of threat to the components (Kent *et al.* 1992; Spencer *et al.* 1998)

Wetland characteristic	Wetland component	Indicators identified	Measure type
Wetland catchment	Wetland catchment	Percentage of native vegetation cover in the catchment	Surrogate
		Percentage of land in different land use intensity classes in the catchment	Surrogate
		Percentage of soil affected by acidification in the wetland catchment	Surrogate
		Percentage of land in different land use intensity classes adjacent to the wetland	Surrogate
	Wetland buffer	Average width of the buffer	Direct
		Percentage of wetland perimeter with buffer	Direct
Physical form	Area of the wetland	Percentage reduction in wetland area	Direct
	Wetland form	Wetland bathymetry	Direct
		Depth of wetland (maximum water depth)	Direct
		Percentage of wetland in which activities (excavation and land forming) have resulted in a change in bathymetry	Surrogate
Hydrology	Water depth; and frequency, duration and timing of inundation	Water depth or surface water extent over time (to establish frequency, seasonality and duration of inundation)	Direct
		Likelihood or severity of change in water regime	Surrogate
		Activities that interfere with natural connectivity of flow to and from the wetland	Surrogate
Water properties	Nitrogen	Nitrogen	Direct
	Phosphorus	Phosphorus	Direct
		Frequency of algal blooms in past 5 years	Surrogate
	Macronutrients (e.g. nitrogen and phosphorus)	Aquatic plant biomass	Surrogate
		Aquatic macroinvertebrate indicator species or index	Surrogate
		Activities leading to an input of nutrients to the wetland	Surrogate
	Electrical conductivity (salinity)	Electrical conductivity	Direct
		Aquatic macroinvertebrate abundance and diversity	Surrogate
		Diatom abundance and diversity	Surrogate
		Vegetation indicator species or communities	Surrogate
		Factors likely to lead to a change in wetland salinity	Surrogate
		Groundwater levels at wetland	Surrogate
	Turbidity	Turbidity	Direct
		Percentage and severity of wetland soil disturbance	Surrogate
	Temperature	Temperature	Direct
		Vegetation cover over water surface (amount of shading)	Surrogate
	Dissolved oxygen	Dissolved oxygen	Direct
	pH	pH	Direct
		Presence or absence of sulfidic soils in the wetland and activities involving the disturbance of such soils	Surrogate
		Presence or absence of acid or alkaline industrial waste discharges into the wetland	Surrogate
		Presence or absence of source of atmospheric acid deposition (traffic, factories, smelters, power stations burning fossil fuels)	Surrogate
	Nutrient cycling	Macroinvertebrate-based index	Surrogate
Wetland soils	Soil physical properties (structure, texture, consistency and profile)	Soil physical properties	Direct
		Percentage and severity of wetland soil disturbance	Surrogate
		Presence of activities that cause soil disturbance	Surrogate
	Soil chemical properties (organic content, nutrients, metal oxides, silica clays, salts and pH)	Soil pH	Direct
		Soil salt levels	Direct
		Soil nutrient levels	Direct
		Presence of toxicants	Surrogate
		Activities leading to an input of nutrients into the wetland	Surrogate
		Factors likely to lead to wetland salinisation	Surrogate
	Soil biological properties (soil organisms such as bacteria, fungi, protozoans, nematodes, mites and worms)	Abundance, diversity and richness of benthic biota	Direct
		Benthic fauna index	Surrogate

(*Continued*)

(Continued)

Wetland characteristic	Wetland component	Indicators identified	Measure type
Biota	Vertebrate fauna (fish, amphibians, reptiles, waterbirds and mammals)	Abundance measures or presence or absence for individual species or indicator (keystone) species	Direct
	Aquatic invertebrates	Measures of species abundance, richness and diversity for particular groups	Direct
	Phytoplankton	Measures of habitat quality for particular groups	Surrogate
	Diatoms	Abundance of pest species	Surrogate
		Abundance of native species	Surrogate
	Wetland vegetation	Individual species cover or biomass	Direct
		Vegetation community attributes such as species richness, critical species or life form presence, cover, structure and health	Direct
		Indicators of altered processes	Surrogate
		Weeds	Surrogate